DEPARTMENT OF THE AIR FORCE
AIR FORCE CIVIL ENGINEER CENTER

21 July 2015

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Mr. Patrick Shinabery
Arizona Department of Environmental Quality
1110 West Washington Street, 4415B-1
Phoenix, Arizona 85007

Subject: Response to 22 June 2015 ADEQ Comments on
WAFB - ADEQ Evaluation of USAF Response to ADEQ Comments
Weekly Progress Report 27 April 2015 and Progress Report 4 May 2015
Steam Enhanced Extraction - Site ST012
Former Williams Air Force Base

Dear Mr. Shinabery:

The Air Force is pleased to submit the attached responses to Arizona Department of Environmental Quality (ADEQ) comments dated 22 June 2015 on the Steam Enhanced Extraction Progress Reports dated 27 April 2015 and 4 May 2015 for Site ST012 located at the former Williams Air Force Base in Mesa, Arizona.

EVALUATION

ADEQ El) Responses to Comments 1, 2, 3, 4

For hydraulic containment during steam injection, the following mass balance relationship applies,
(Extraction Rate)> (Injection Rate + GW Encroachment + Steam-Displaced Groundwater)

$$\dot{m}_{extract} > \dot{m}_{inject} + \dot{m}_{encroach} + \dot{m}_{displace}$$

$$\frac{\dot{m}_{extract}}{\dot{m}_{inject} + \dot{m}_{encroach} + \dot{m}_{displace}} > 1$$

The mass displacement rate is a function of the growth rate of the steam zone and accounts for phase change according to energy and volume balances. The encroachment accounts for natural groundwater flow. The injection parameter accounts for steam condensate.

Because the steam condenses, there is no reliable way to calculate or measure the actual steam volume in the formation.

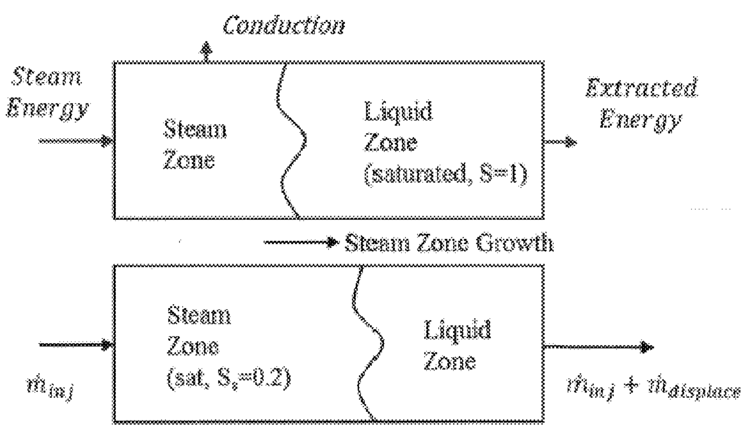
This is contradictory to the statement in the SEE Work Plan, Appendix D, p10,

"The injection of steam is a stable and predictable process. The steam propagation is governed by heat transfer to the formation, which has been studied intensively for oil recovery and has been applied to remediation applications for over 20 years."

A straightforward method to estimate steam zone volume and growth during injection is provided in the attached document, "Evaluation of Hydraulic Containment during Steam Enhanced Extraction." The method has been published in numerous references over the last 50 years (e.g., Marx & Langenheim, 1959; Mandl & Volek, 1969; Yortsos, 1982; Menegus & Udell, 1985). Application of the method to ST012 is also provided in the TEE Pilot Study Work Plan, Appendix C and in the TEE Pilot Study Evaluation Report, Appendix I. Use of the method as input to MODFLOW for assessing hydraulic containment is provided in the TEE Pilot Study Evaluation Report, Appendix H.

The method includes energy injection, energy extraction, and thermal conduction into fine-grained confining layers and combines mass and energy balances to estimate the growth of the steam zone and the rate of groundwater displacement during growth. As described in the cited attachment, combined mass and energy balances yield a single equation,

$$\frac{\dot{m}_{displace}}{\dot{m}_{inj}} = \frac{(1-S_S)\left[1+\frac{h_{fg}}{c_{pw}(T_S-T_0)}\right](1-F_{ext}-F_{cond})}{\frac{\rho_r c_{pr}(1-\varphi)}{\rho_w c_{pw}\varphi}+S_S+(1-S_S)\frac{\rho_v}{\rho_w}\left[1+\frac{h_{fg}}{c_{pw}(T_S-T_0)}\right]}-1$$



F_{ext} and F_{cond} represent energy extraction and thermal conduction rates, respectively, relative to the energy of steam injection. As provided in the attachment, substituting LSZ-specific parameters into this equation yields an expression for hydraulic containment during steam injection,

$$\frac{\dot{m}_{extract}}{\dot{m}_{inj} + \dot{m}_{encr} + \dot{m}_{inj}[2 - 3(F_{ext} + F_{cond})]} > 1$$

Response:

The Air Force (AF) agrees in principle with the reference and this reasoning. Empirical calculations can serve as a line of evidence in determining steam movement; however, the calculation is subject to the limitations of the data collection and inputs that were not specifically designed to support this type of detailed analysis. The effects of these limitations, which results in an overestimation of energy input when correlated to actual observed operational conditions, does not significantly contradict site conditions (subsurface temperatures and steam breakthrough to many wells in the LSZ and UWBZ). Based on operational data indicating steam breakthrough, the AF initiated depressurization in early June.

The operation of the SEE system over the duration of the project has maintained an extraction to injection ratio greater than 2:1 (over 3.6:1 in the UWBZ). Based on the observed hydraulic containment reported in the weekly reports, the ratio is sufficient to account for injection, encroachment, and displacement.

TerraTherm considers a ratio of 1.25:1 to be a minimum and prefers to operate at ratios of 1.5:1 and higher.

Data from weekly progress reports were used as input into the mass ratio expression above. Separate calculations for the LSZ and UWBZ were performed with data and parameters approximated from Figure 17 and Figure 21. The parameters and results are provided below. As indicated, initial extraction rates were much lower than required to contain the applied steam injection rates. Containment conditions are improved recently as a result of energy extraction but hydraulic containment has not been maintained in either zone during the operating conditions shown below. On 6/1/15, the LSZ extraction rate required to achieve a net ratio of 1.5 in the LSZ was about 120 gpm (205 gpm overall) and on 6/8/15 the LSZ extraction rate needed to be about 150 gpm (275 gpm overall) for hydraulic containment during the reported steam injection rates. However, the assumed thermal conduction rates are likely overpredicted.

Mass & Energy Balances for Hydraulic Containment

Week	Extraction $\dot{m}_{extract}$	Injection $\dot{m}_{inject}$	GW Flow $\dot{m}_{encroach}$	F_{ext} $\dot{E}_{ext}/\dot{E}_{inj}$	Displace $\dot{m}_{displace}$	Net Ratio
OVERALL	(incl CZ ext)					
11/23/14	126	66	12	0.05	82	**0.79**
12/1/14	129	65	12	0.08	75	**0.85**
12/8/14	161	72	12	0.07	85	**0.78**
12/15/14	142	75	12	0.09	86	**0.82**
6/1/2015	120	73	12	0.40	36	**1.00**
6/8/2015	101	70	12	0.25	66	**0.68**
LSZ						
11/23/14	82	66	7.5	0.05	82	**0.53**
12/1/14	81	65	7.5	0.08	75	**0.55**
12/8/14	85	64	7.5	0.09	72	**0.59**
12/15/14	96	61	7.5	0.11	66	**0.72**
6/1/2015	70	49	7.8	~0.40	24	**0.86**
6/8/2015	55	48	7.8	~0.25	45	**0.55**
UWBZ						
12/8/14	28	15	4.2	0.00	21	**0.70**
12/15/14	31	14	4.2	0.00	20	**0.79**
6/1/2015	41	23	4.2	~0.40	11	**1.06**
6/8/2015	38	23	4.2	~0.25	21	**0.79**

Values listed are in gallons per minute equivalent based on a water density of 8.35 lbs/gallon

$\dot{m}_{displace} = \dot{m}_{inj}[1.4 - 3F_{ext}]$ for 20% conduction during early steam injection

$\dot{m}_{displace} = \dot{m}_{inj}[1.7 - 3F_{ext}]$ for 10% conduction at later times when clays are heated

Response:

As indicated previously, the data collected is not specifically intended to support the type of analysis presented in the calculations above and will limit the calculation accuracy as well as conclusions based on the above analysis. The operational plan is not based on instantaneous control of displacement at any point in time but overall hydraulic control of groundwater through the duration of the project. As such ratios less than 1.0 (including displacement) are acceptable during steam bubble expansion provided that operational data indicates an overall inward gradient at the site perimeter. The following further explains some of the basis of the operational plan.

Limited Mobilization along the Perimeter

The SEE basis of design included a 10 m (33 ft) steam zone along the outside of the treatment zone with the movement of steam and hot water along the perimeter of the treatment zone. The hot water zone naturally extends beyond the 10 m steam zone especially in areas with perimeter steam injection. The SEE design also includes a post-SEE extraction period. In this period the volume displaced by the steam (as indicated in the calculations above) will collapse and allow the same amount of water as was previously displaced to flow back into the treatment zone for collection and treatment by the SEE extraction system. A similar collapse occurs on a smaller scale during the depressurization phase of a pressure cycle.

Hydraulic Gradient

The SEE hydraulic containment system was brought online on 29 September 2015 and operated in the LSZ without steam injection until 16 October 2015 and in the UWBZ without steam injection until 5 December 2015. The table below shows the observed hydraulic responses in the perimeter wells (pre-steam injection) and the average hydraulic response (i.e., change in level [ft] from baseline) after steam injection in the two zones was initiated. The table below also shows the calculated percentage of measuring rounds (typically on a weekly basis) that the measured depth to water in these wells was below the measured baseline level.

Monitoring Well	Average Change from Baseline during Startup of Hydraulic System until Steam Startup [ft]	Average Change from Baseline during Steam Period [ft]	Percent of Groundwater Level Measuring Rounds with Lower than Baseline Water Levels
ST012-RB-3A	-1.35	-0.80	91%
ST012-U02	-1.19	-0.56	79%
ST012-U11	-1.35	-0.82	88%
ST012-U12	-1.35	-0.93	79%
ST012-U37	-1.68	-0.85	88%
ST012-U38	-0.96	-0.56	91%
LSZ Wells			
ST012-W11	-1.69	-1.65	85%
ST012-W12	-1.69	-1.40	83%
ST012-W24	-1.60	-1.23	85%
ST012-W30	-1.33	-0.45	58%
ST012-W34	-1.41	-0.96	80%
ST012-W36	-1.49	-0.57	56%
ST012-W37	-2.03	-1.41	90%
ST012-W38	-1.28	-0.92	88%

As seen in the table above, the gradient during SEE operation has generally been inward. Higher than baseline perimeter water levels have generally corresponded to periods of aggressive steam injection and the increased water levels are temporary.

TerraTherm has looked more closely at the two perimeter wells with higher instances of increased water levels as compared to baseline conditions –W30 and W36. W30 is located upgradient to the treatment zone and mobilized contamination will flow back into the treatment zone during times of depressurization and post-SEE extraction. W36 is a monitoring well located approximately 150 ft from perimeter steam injection well LSZ18 which was identified as having limited NAPL impacts during well installation and final SEE well determination (based on actual observations during well installation –including staining, odor, NAPL test results and PID readings). Because of the limited NAPL observed at this location, LSZ18 was selected as a steam injection well. As stated above, these water level increases are temporary and show a hydraulic response to steam injection. As recently as June 26, 2015, water levels in W30 and W36 were measured at 5.73 and 5.42 feet below baseline, respectively (due to depressurization and the resulting hydraulic response).

Site Water Balance

To date, 14,425,000 gallons have been extracted from the UWBZ while 3,900,000 gallons have been injected as steam; in the LSZ, 32,275,000 gallons have been extracted while 14,354,000 gallons has been injected as steam. The extraction and injection totals correspond to extracting approximately 3.69 gallons per gallon injected in the UWBZ and 2.25 gallons extracted per gallon injected in the LSZ. If one considers only the water extracted in the active steam injection period (i.e., only the water extracted after steam was initiated in the two zones), then the gallons extracted per gallon injected for the UWBZ and LSZ would be 2.90 and 2.18, respectively.

Extraction numbers are based on individual eductor flowmeters which have been found not to align 100% with the site main flowmeters, however the net extraction is still well above the injection rates. Additionally, the steam injection rates are also based on individual steam flowmeters that, per experience, also have some uncertainty associated with the measurements. Calculations based on natural gas used by the boilers indicate that, if anything, the stated injection rates are less than assumed in these water balance calculations. Also, the post-thermal water extraction period will only add extra contingency to the total site water balance during the thermal remedy.

Post-Thermal Bioremediation

The post-SEE enhanced bioremediation (EBR) phase will be designed to address residual contamination both within and outside of the SEE TTZs. The removal of NAPL from wells W11, W30, and W37 represents mass removal from locations that had detected NAPL prior to SEE. There is a benefit to the EBR phase to collect NAPL from these areas to reduce the contaminant mass that must be biologically degraded. Increased dissolved phase contamination around the site periphery also makes the contaminants more accessible for biological degradation in the subsequent EBR phase and identifies areas around the perimeter that suggest NAPL in the proximity that will need to be addressed by EBR. The EBR plan is currently in design and is likely to include a component of injection of terminal electron acceptor in the LSZ around the site perimeter with extraction in the site interior. This action will work to both pull contamination back toward the site and provide treatment in the area around the TTZ.

Summary

In summary, instead of basing operational decisions on theoretical calculations, TerraTherm has used operational data and observations to guide operational planning and decision making. While the calculations carry assumptions and large uncertainties, operational data are the most reliable tools for decision making during remedy implementation.

ADEQ E2) Responses to Comments 5 and 6

LSZ10, LSZ23 LSZ09 and LSZ27 are in upgradient locations of the site and do not pose similar potential for downgradient off-site migration.

Steam injection continued in LSZ09 although LSZ37 was not operating and required repair. The lack of extraction and containment in LSZ37 likely resulted in the NAPL accumulation in W30, upgradient of both the TTZ and HZ.

Response:

On 11 June 2015, operational personnel confirmed that MPE well LSZ37 was not pumping and in need of repair. Operational personnel collected vapor temperatures at the well and review of the vapor temperatures and nearby temperature monitoring (including the collocated array) showed temperatures at boiling, thus the well was not able to be immediately repaired. Operational personnel began ramping down steam injection at LSZ09 on 11 June 2015 and continued to ramp down injection as temperature readings collected from LSZ37 continued to show a pattern of sporadic boiling temperatures that were not conducive to pulling the pump assembly from a health and safety standpoint. Overall steam injection at LSZ09 was ultimately ramped down to approximately 80% of the original injection rate (i.e., ramped down to approximately 1500 lbs/hr). On 22 June 2015, steam injection to the LSZ was decreased to a minimum to initiate a depressurization cycle. MPE wells LSZ08, LSZ30 and LSZ38 surrounding LSZ09 to the north, east and south, respectively, were still pumping through this period.

SIW LSZ09 is more than 150 feet away from W30. It is highly unlikely that NAPL travelled 150 feet upgradient of the site to the W30 location. It is much more likely that NAPL outside of the TTZ (as has been detected in W30 prior to the startup of the SEE system) is being collected at W30 due to hydraulic changes around the SEE treatment zone allowing it to be pumped out and removed.

Similar adjustments may be made at LSZJ8 and/or LSZ22 based on temperature increases at TMP2.

The benzene concentration in W34 is rising, well beyond the TTZ and HZ supporting the original comment to consider reducing or terminating injection at LSZ18 and reducing injection in LSZ22.

Response:

Steam injection rates were reduced by approximately 15% beginning on 2 June 2015 at SIW LSZ18. Steam injection rates were reduced by approximately 40% at SIW LSZ22 on 27 May 2015. A depressurization cycle of the LSZ began on 16 June 2015 with complete steam turn down in this zone on 22 June 2015. Also, as described above, the water levels in W34 have generally been below baseline levels in 80% of the groundwater measurement rounds during operations (at times by several feet). This indicates a flow direction toward the treatment zone at this location.

ADEQ E3) Response to Comment 7

Only limited steam breakthrough has occurred in the LSZ to date, so contaminant mass removal has not likely peaked.

According to the most recent weekly progress report (Table 4), steam is currently present in 8 of the 27 LSZ extraction wells and steam has appeared previously in an additional 10 of the wells. 18 of 27 LSZ extraction wells have experienced steam breakthrough.

Response:
The original response is now somewhat dated as remediation has progressed. The AF continuously evaluates individual extraction well temperatures and corrects for the fact that steam, after reaching a well screen, can condense in the casing on the way to the surface. The eductor pumps have a feed water loop with approximately 10 gpm of cooled water entering from the surface which is essentially acting as a heat exchanger/condenser and therefore steam can be present at the screen depth without making it out to top of the well. The condensed steam will instead be extracted with the water, and the energy is counted in the liquid stream. Steam can also flow directly into the eductor and then condense inside the discharge line. As a result of these individual well evaluations, steam breakthrough was observed at additional extraction wells, and when the operational data warranted it, the AF initiated depressurization in the appropriate zones.

ADEQ E4) Response to Comment 8

Has steam injection been reduced accordingly in nearby injection wells LSZ09 and LSZ23? No.

As stated above in Comments 5 and 6, the lack of extraction and containment in LSZ37 has likely caused the NAPL accumulation in W30, upgradient of the TTZ and HZ.

Response:
The AF disagrees with the response above. NAPL was present in W30 before SEE extraction or injection began.

Please contact me at (315) 356-0810, ext. 204 or catherine.jerrard@us.af.mil if you have any questions regarding this report.

Sincerely,

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